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Wick type solar stills: A review

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ABSTRACT

Solar distillation is one of the water purification techniques that produce ultrapure water which is superior to most of the commercial bottled water sources. Though solar distillation is a simple method, productivity seems to be low due to the large thermal capacity and consumption of time. Researchers have taken efforts to make different designs of solar still for higher distillate yield and inferred that wick-type solar stills are effective and efficient. In this review, we are making an attempt to study the present status of different designs of wick type solar stills.

Contents

1. Introduction

People prefer technologies whenever they find something lacking in their life. Solar distillation is one such technology, which they found useful as a solution for their drinking water shortages. Though the availability of global water reserves is about 1.4 billion km^3, the sea water constitutes about 97.5%. Only the remaining 2.5% is gifted as fresh water for human beings and other living organisms. The available amount of fresh water in the

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Nomenclature

ΔY	thickness of water layer, (m)
ρw	density of water, (kg/m^3)
c_{pw}, c_w	specific heat capacity of water (J/kg K)
$\Delta\tau$	time interval selected (2 min), (m/s)
U_2	overall heat transfer coefficient between bottom wall and surrounding (W/m^2 °C)
A_s, A	area of the still (m)
A_m	Area of the mirror (m^2)
m_i	hourly productivity (l)
P_d	daily productivity (l/m^2 day)
kw	thermal conductivity of water (w/m K)
h_1	total heat transfer from water to glass cover (W/m^2 °C)
h_2	heat transfer from floating-water to ambient (W/m^2 °C)
h'_2	heat transfer coefficient from glass cover to flowing water (W/m^2 °C)
T_g, T_w, T_a	glass, water and ambient temperatures (°C)
$\overline{T}_g$	average water temperature (°C)
$\overline{T}_g$	average glass temperature (°C)
T_{w1}	temperature of the flowing water over the glass cover (°C)
m_w	mass flow rate of water over the glass cover (kg/s)
τ	fraction of energy absorbed by water in still
L, l	latent heat of evaporation (J/kg °C)
$\in_\omega$	emissivity of water surface
σ	Stefan–Boltzmann constant, 5.669×10^{-8} (w/m^2 °C^4)
m_{ew}	amount of water distillate per unit time per unit basin area (kg/m^2 s)
q_u	the rate of heat loss due to water flow
P_w, P_g	saturated vapour pressure of water and glass (N/m^2)
h_{rw}, h_{ew}, h_{cw}	radiative, evaporative and convective heat transfer coefficient (W/m^2 °C)
η_o	overall efficiency of the distillate output
α_g	absorptance-transmittance product of glass cover
b_3, b_3, b_1	breadth of the glass cover, tilted, floating-wick surfaces (m)
dx_3, dx_2, dx_1	length of the glass cover, tilted, floating-wick surfaces (m)
h_1	total heat transfer coefficient from tilted-wick surface to glass (W/m^2 °C)
h_2	total heat transfer coefficient from floating-wick surface to glass (W/m^2 °C)
h_3	total heat transfer from glass surface to ambient (W/m^2)
T_g, T_{w1}, T_{wf}	temperature of glass, tilted, floating-wick, ambient (°C)
α_{w1}	absorptivity of blackened tilted-wick surface
m_{w1}	mass flow rate along the tilted-wick along the length L_1 (kg/s)
$\overline{T}_g$,$\overline{T}_{w1}$,$\overline{T}_{wf}$	average temperature of the glass, tilted and floating-wick surfaces (°C)
L_1, L_2	length of the tilted and floating-wick stills (m)
h_4	convective and radiative heat transfer coefficient from flowing water to ambient (W/m^2)
θ_{evap}	evaporative heat transfer from flowing water to the ambient (W/m^2)
m_{fw}	mass of the flowing water over the glass cover (kg/s)
T_{fw}	temperature of the flowing water over the glass cover (°C)
A_{wf}, A_{w1}	area of floating and tilted-wick surfaces (m_2)
h_{ewfa}	evaporative heat transfer coefficient form floating-wick to ambient (W/m^2)
$Q_{sun,re}$, $Q_{sun,re}$, $Q_{sun,df}$	rate of absorption of reflected, direct and diffused solar radiation (W)
G_{dr}, G_{df}	direct and diffused solar radiation on a horizontal surface (W/m^2)
$Q_{sun,g}$, $Q_{sun,w}$	absorption of solar radiation on glass and wick surfaces (W/m^2)
τ_g	transmittance of glass cover
β	incident angle of sunrays to glass cover (°)
β'	incident angle of reflected sunrays to glass cover (°)
ρ_m	reflectance of reflector
α_w	absorptance of the wick
w	width (m)
m_{cp}	heat capacity (J/K)
l_s	length of the still (m)
Q_{ci}, Q_{ei}, Q_{ri}	convective, evaporative and radiative heat transfer from water to glass cover (W/m^2)
h_{ci}, h_{ri}	convective and radiative heat transfer coefficient from glass cover to ambient (W/m^2)
Si	computation ratio (heat of evaporation to total heat transferred)
Q_{ac}	heat transferred from ambient to glass cover (W/m^2)
Q_{be}	conduction heat transfer through base (W/m^2)
h_{ca}	heat transferred from glass cover to atmosphere by convection (W/m^2)
h_θ	latent heat (kJ/kg)
H_s, $I(t)$, S	incident solar radiation on glass cover per unit area per unit time (W/m^2)
M	mass of the water (kg)

form of rivers, lakes, surface water, polar ice, ground water etc., cannot match the water requirement for the entire globe. Hence solar distillation can be considered as a practical alternative for the production of drinking water.

2. Working of a wick type solar still

The solar radiation falling on the glass cover transmits through it and reaches the wick surface, where it is absorbed. A part of the energy is utilized for heating the water flowing through the wick due to capillary action. A large amount of heat gets trapped inside the still, and transfer of energy takes place from the wick surface to the glass cover and to the ambient air. Heat transfers in the distillation system are governed by external and internal modes. The external heat transfer mode occurs due to convection and radiation, which are independent of each other and occurs outside the still. Heat transfer within the solar distillation unit is referred to as the internal heat transfer mode, which occurs due to radiation, convection and evaporation. In internal heat transfer mode, the mass transfer accompanied with radiative and convective heat transfer. Water flowing through the wick surface gets heated and evaporated into vapors. The saturated water vapour condenses in the lower surface of the glass cover after releasing the latent heat of vaporization. The condensed water droplets trickle down due to gravity and get collected in the drainage channel.

3. Review

3.1. Various designs of wick-type solar stills

Various designs of wick type solar stills

Basin wick type [1–3]
Wick-basin type [4]
Floating-wick type [5,6]
Multi-wick type [7–10]
Floating cum tilted-wick type [11,12]
Tilted wick-type with flat plate reflectors [13–17]
"V" type solar still with-wick as absorbing material [18]
Concave wick-type [19]
Single basin wick type
With fin [20]
Clothes moving wick-type [21]
Double slope wick type [22]

3.1.1. Basin wick-type solar stills

Researchers have designed different designs of basin wick-type solar still [1–3]. The basin wick-type solar stills, with jute and charcoal as wick materials, are very simple in construction. The system consists of a simple basin enclosed in a thermally insulated wooden box and covered by a glass. Jute wick material [1,2] is floated on the basin water and charcoal wick material [3] is introduced in the tilted basin and analyzed. The analyses have been carried with the following assumptions:

- The wick type solar still is made vapour tight.
- The absorptivity of glass cover and water are negligible.
- The stills are perfectly insulated.
- The wick material used is blackened for more absorption.
- The heat capacity of the glass cover and insulating material of the solar still are negligible.

3.1.1.1. Working. The jute wick material [1,2] in the basin sucks water and due to capillary action, the upper surface of the wick material is always wet during peak sunny hours. The water gets evaporated and the water vapour condensed in the condensing surface which is pure distilled water. The thermal capacity of the still is less as the jute wick is floated in the basin water. The charcoal wick material [3] introduced in the tilted basin acts as the evaporating surface during the working hours of the still and water flows throughout the wick material due to good capillary action which serve as thin film of water surface for evaporation.

The schematic diagram of the design proposed by Mahdi et al. [3] is shown in Fig. 1 which is provided with an option of changing the angle of inclination of the still for maximum interception of solar radiation. Results [1–3] of the study show that the wick-type solar still is more effective than the conventional basin type solar still due to limited thermal capacity.

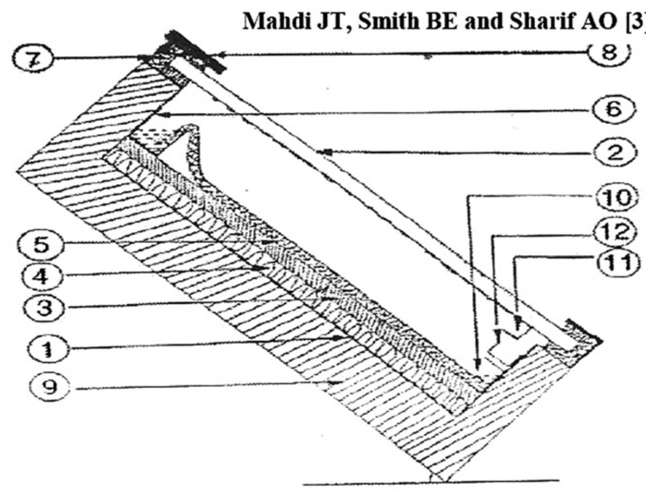

Fig. 1. Cross sectional view of the still. (1) Galvanished steel tray, (2) glass cover, (3) support board, (4) polystyrene, (5) charcoal cloth, (6) aluminium channel, (7) rubber gasket, (8) steel strip, (9) Styrofoam, (10) brine gutter, (11) distillate gutter and (12) distillate outlet channel.

3.1.2. Wick-basin type solar still

The wick-basin type solar still designed by Minasian and Al-Karaghouli [4] has great potential because of high productivity than the other types of basin and wick type stills. The still construction is simple. The basin and the wick type are integrated to form a wick-basin type still. The design parameters of the still are given in Table 1. The still consists of metallic basin made of galvanized iron sheets (22 gauge) and glass cover. The bottom and side are insulated. The black painted wick is enclosed by a wooden frame.

3.1.2.1. Working of the still. The preheated water during the working hours of the tilted-wick type solar still is fed into the conventional basin type solar still through a pipe. Thus the two parts of the still works together assingle unit. The schematic diagram of the wick-basin type is shown in Fig. 2.

3.1.3. Floating wick type solar still

A floating wick type solar still was proposed by Al-karaghouli and Minasian [5] with blackened jute wick and aluminium black plate as floating materials inside the still (Safwat Nafey et al. [6], Fig. 3). The construction of the still is simple and can be done by locally available materials. The design parameters of the still are given in Table 1.

3.1.3.1. Working. The working of the still is similar to that of the conventional type solar still and a flat mirror over the still provides additional advantage to the still with jute wick [5] and shown in Fig. 2.

The jute wick has been prepared in a corrugated shape and made to float in the basin water. The floating wick receives the radiation through the glass cover and reflected by the flat mirror. The wick absorbs solar radiation and heats the water in the wick. The water gets evaporated and the water vapour condenses in the lower side of the condensing glass cover as pure distillate yield. Due to the corrugated shape of the wick, the salt deposited in the lower side of the wick and the salt diminished water flows through the upper surface of the wick.

Experimental investigations have been carried out with the still and the conclusions arrived at are:

- Single slope solar still gave a better output yield of 10.5 l/m^2 than any other still with jute cloth as absorbing medium.
- Placing a flat mirror over the still has led to the increased evaporation rate and distillate yield.
- Blackened jute wick shows high yield, compared to the still with aluminium perforated black plate.

Numerical calculations [6] have been made by writing energy balance equations for glass cover, moist air, water liner, floating black plate, top layer of water block, *n*th water layer, and bottom layer of the water block and for basin liner. To achieve stability of numerical solution, the water layer thickness has been calculated

Table 1
Comparison of different designs of wick type solar stills.

Type of still	Reference no.	Geometry	Results	Advantages	Disadvantages
Wick type stills	[1]	• Jute wick is used • Inclination 10° • Area is equal to the area of the wick. • Insulation thickness 0.044 • Length is 0.62 m.	It is observed that the distillers without insulation produce lower yields.	The cost of this type of stills is less than half in comparison with a basin type still of same area. But the production is high.	Without insulation the output yield is very low.
	[2]	• Jute wick is used. • Inclination 10°, 20°, 30° and 40° were tested. • Area = 1 m^2. • Insulation thickness = 2.50. • Glass cover thickness = 5 mm.	With different angle studies, 10° gives more output in summer and 40° gives more output during winter.	At lowest angle, the still yielded maximum of 3400 ml.	The still is not portable is the only disadvantage.
	[3]	• Charcoal cloth is used. • Bottom insulation with Styrofoam of 35 mm. • Insulation = 25 mm • Glass thickness = 4 mm.	The still efficiency has decreased from 38% to 20% when the salt concentration is increased from 0.0% to 10%.	Outdoor test results have shown higher efficiency than indoor tests.	Increasing the surface tension of the salty water during the evaporation process decreases the evaporation rate and the still efficiency.
Wick-basin type	[4]	1. Conventional basin type • Area of the basin = 0.8 × 0.5 m^2. • Glass thickness = 4 mm. • Inclination = 15°. • Bottom insulation = 5 cm. • Side insulation = 1 cm. 2. Wick type still • Blackened jute cloth is used. • Area = 1 m^2. • Glass thickness = 4 mm. • Inclination = 25° (summer) = 45° (winter).	The wick-basin type solar still is economical as well as efficient than basin type and wick type stills.	Wick basin type productivity is 85% more than basin type and 43% more than wick-type solar stills.	Individual performance analysis of these stills may result in efficiency drop down.
Floating wick type solar stills5	[5]	• Blackened jute wick is floated with a polystyrene sheet. • Area of the basin is 0.8 × 0.6 m^2. • Glass thickness = 4 mm. • Insulation thickness = 5 cm.	The good capillarity of the floating wick fibres have ensured that the entire surface of cloth irradiated by the sun is wet all the time.	The maximum daily output of the proposed still is 10.51 m^2.	Controlling the accumulation of salt on the wick surface is the major problem.
	[6]	• Floating perforated black aluminium plate of 0.5 mm is used. • Insulation thickness 4 cms. • Glass thickness = 3 mm. • Inclination 15°.	The higher productivity is obtained in the higher brine depth.	Using a floating perforated plate in solar still at a brine depth of 6 cm enhanced the productivity.	Maintaining the depth of brine water is quite risky.
Multi-wick type solar stills, wick-type still with effect of	[7]	• Polytetrafluoroethylene is used between evaporative and condensing wick.	The experimental values are generally in good agreement with the predictions.	The distillate obtained in the present experiment is found to contain less than 10ppm salt, and this value is perfectly acceptable.	The low productivity of 10 mm gap still is due to largest heat loss from solar absorber to the ambient air and its large heat flux Q_f.

Table 1 (*continued*)

Type of still	Reference no.	Geometry	Results	Advantages	Disadvantages
water flowing over the glass cover.		• Area $=0.3\times0.42$ m^2. • Top insulation $=70$ mm. • Area of the top most insulation layer $=0.46\times0.51$ m^2.			
	[8]	• Blackened overlapped wicks separated by polythenes sheets are used. • Insulation thickness $=0.05$ m.	The output is increased by approximately 10%.	As the flowing water over the glass cover takes away the latent heat of glass cover, more distillate is obtained.	There may be increase or decrease in distillate output with increase or decrease in the heat transfer coefficient from glass cover to water flowing over it respectively.
	[9]	Single slope multi-wick still: • Jute cloth wicks (porous fibres) are used. • Area of the still is 1 m^2. • Inclination angle $=15^\circ$. • Insulation thickness $=5$ mm • Oriented due south. Double slope multi-wick still: • Jute wicks are used. • Oriented due east-west direction. • Glass cover of area 1.1×1.1 m^2 placed each side.	The inner and outer glass temperature is more prominent in summer in comparison to winter.	In winter single slope solar still gives more efficiency and in summer multi-wick double slope still gives more efficiency.	More reflection loss takes place in double slope stills in winter and in single slope the reflection loss takes place in summer.
	[10]	• Jute cloth (kept vertically) is used. • Inclination angle $=25^\circ$. • Glass thickness $=0.003$ m. • Area of the still $=1\times0.5$ m^2.Still is placed along east-west direction and the glass cover inclines south.	The rate of evaporation of water vapour from the water surfaces depends on the rate of water vapour in the glass cover and temperature difference between the saline water and glass cover.	Independent water production, and maintenance-less device.	Low efficiency, problem of salt deposits, deposit of scale and corrosion. If there is no sunshine, the yield will be zero.
Floating cum tilted wick type solar stills	[11]	• Blackened jute wick is used. • Inclination angle $=15^\circ$. • Glass cover thickness $=4$ mm.	Under this both closed cycle system and open cycle system, the overall efficiency for the closed cycle system shows increasing values than open cycle system as expected.	Three problems have been overcome in this article. (i) Wick getting dryness during working hours of the still has been solved, (ii) excess heat losses have been solved by feeding excess hot water to the reservoir and (iii) salt formation in tilted portion is avoided because it forms in the lower part of the floating wick itself.	The instantaneous efficiencies for both the cycle is almost constant during the lowest flow rate of water to the reservoir (i.e.,) at 10 am to 2 pm.
	[12]	• Blackened jute wick is used. • Inclination angle $=15^\circ$. • Glass cover thickness $=4$ mm • Water flow rate over the glass cover $=1.5$ m/s.	The effect of water flowing over the glass cover have some fascinating effect and the water flow rate of 1.5 m/s is founded to be the optimum water flow rate over the glass cover.	Water flowing over the glass covet utilizes more heat from the glass cover for fast evaporation during the working hours of the system.	Zero night time collection.
Tilted wick type still with flat plate collectors	[13]	• Area $=1$ m^2. • Inclination: with reflector $=20^\circ$. • Without reflector $=30^\circ$. • Bottom insulation thickness $=50$ mm.	The vertical flat plate external reflector would be less effective for the tilted wick still than for the basin still.	The average daily amount of distillate of the still with reflector is predicted to be about 9% larger than that of the still without reflector.	The still without reflector gives equal output as still with reflector only when the angle (θ) of the still is kept on increasing.

	[14]	• Area $=1\times1$ m^2. • Orientation faces due south. • Area of the reflector is half the area of the basin of the still. • Different inclinations 10°, 20°, 30°and 40° have been tried. • Reflector inclination $=15°$ from vertical.	The external reflector inclination is set about 15° from vertical have produced 16% increase in distillate over a basin type still.	The daily amount of distillate produced by a tilted-wick still can be increased by inclining the reflector as well as increasing the length of the reflectors.	The benefit of a vertical flat plate external reflector would be loss for a still with a larger slope (or) inclination angle more than 35°.
	[15]	• Area $=1\times1$ m^2. • Insulation thickness $=50$ mm. • Orientation: ($-45°$) morning $=$ south east ($+45°$)noon $=$ south west • Ordinary inclination of the still is 30°.	When $\theta>40°$, all of the reflected solar radiation from the vertical reflector cannot hit the still and would escape to the ground throughout the day, so the use of reflector would be negligible even for the rotated still when the still angle $\theta>40°$.	The daily amount of distillate produced by the tilted-wick still can be drastically increased by using a vertical flat plate reflector.	The distillate production rate is smaller for the rotated still than for a fixed still around noon, but increases around the peak times in both the morning and the noon.
	[16]	• Area $=1\times1$ m^2. • Insulation thickness $=50$ mm. • Orientation $=$ due south. • Bottom reflector angles at (20°) $=$ during winter solstice (30°) $=$ during spring and autumn, (50°) $=$ during summer solstice. • Ordinary inclination of the still is	The daily amount of distillate output has been obtained greatest when the inclination angle θ_m of the bottom reflector is adjusted in positions according to the seasons.	By adding bottom reflector to the still, the distillate yield is highest on summer solstice (25%).	With different inclination angles in the experiment 35° is the only angle found optimum and the rest are low yielding ones.
	[17]	• Area $=1\times1$ m^2. • Area of the reflector $=0.5\times1$ m^2. • Bottom insulation thickness $=50$ mm. • Slope of the still $=30°$. • Reflector inclination less than 25° is optimum.	The optimum inclination angled of the still would be smaller in summer (10°) and larger in winter with the slope (50°).	By using the reflector in conventional tilted wick still and with inclination adjustments according to months, yielded an average efficiency of about 21% throughout the year.	The adjustments of the slope of the reflector have been made manually is the disadvantage.
"v" type solar still using charcoal as absorber	[18]	• Charcoal absorber is used. • Area of the basin $0.50\times0.50\times0.15$ m^3. • Distillate collector area $=0.03$ m. • Glass cover thickness $=2$ mm • Slope of the still $=22°$ • Glass width $=0.27$ m • Booster mirror area $=0.40$ m^2. • Distillate collector slope $=2°$.	The increase of temperature in the still with the boosting mirror is comparatively more than for the system without the boosting mirror. The floating charcoal increases the absorption of radiation in the water and it results in increasing the evaporation rate.	The small size of the still makes it get heated soon during working hours of the still and the performance ratio increases due to the increase in temperature inside the still.	Though the yield was more, the efficiency of the system is less with the boosting mirror because of high temperature overall loss is more and night time distillate yield is very low.
Concave wick evaporation solar still	[19]	• Jute wick in concave shape is used. • Basin area $=1.2\times1.2$ m^2. • Insulation thickness $=5$ cm. • A sheet insulation of 2 mm surrounds the still. • Thickness of the wick $=5$ cm.	The wick concave solar still output is 200% and instantaneous efficiency with about 50% higher than the conventional type solar stills.	Use of concave wick enhanced solar radiation absorption and the concave still design reduces the shading effect because all sides are made of glass.	The instantaneous efficiency seems to be constant after 3 pm.

Table 1 (*continued*)

Type of still	Reference no.	Geometry	Results	Advantages	Disadvantages
		● Glass cover thickness = 3 mm. ● Slope of the still is 45°.			
Single basin type with fin	[20]	● Area of the basin = 1 m^2. ● Area of the basin with fins 1.0045 m^2. ● Still inclination is 10°. ● Oriented towards north–south direction. ● Saw dust is used as bottom insulating material.	The still with sponges, wick and fins were tested and the still with fins is found efficient.	The efficiency of the still is greater (45.5%) than the sponge test and wick test.	Experimental results have shown higher distillate yield for the still with fin.
Cloth moving wick type solar still.	[21]	● Black cloth is used. ● Area of the basin = 0.50 × 0.50 × 0.15 m^3. ● Still inclination is 30°. ● Oriented due south direction. ● Area of the wick is 0.25 m^2.	Results show that an ON period, 30 s is suitable and an OFF period of 25 min yields maximum thermal efficiency.	Cloth is immersed in water when the motor is ON, and the wet cloth is subjected to solar radiation when the motor is in OFF period.	The problem is low productivity.
Single basin double slope solar still	[22]	● Black light cotton cloth, jute wick, sponge pieces were used. ● Area of inner basin 2.08 × 0.84 × 0.075 m^3. ● Area of outer basin 2.3 × 1 × 0.25 m^3. ● Glass cover thickness 4 mm.Slope of the still 30°.	The still with black light cotton cloth is found more effective out of jute wick, sponge, quartzite rock and washed natural rocks were used as absorbing material.	A new wick material i.e., black cotton cloth has been used and found effective for stills than any other materials.	Basin water depth should have to be noticed carefully because it is the main parameter that affects the performance of a still.
Review papers	[23,24]	● Usually jute cloth is highly used material. ● Optimum glass thickness used is found to be 4 mm. ● Slope of the still that yielded maximum is 30°, and 10° in winter , 40° in summer.	Use of wick materials in various types of the stills has increased the performance and efficiency of the still.	The mass of the distillate yield is maximum compared to that of other basin type stills.	The slope angles variations in some stills may give less production. So it must be checked and applied to the designs which are going to be constructed.

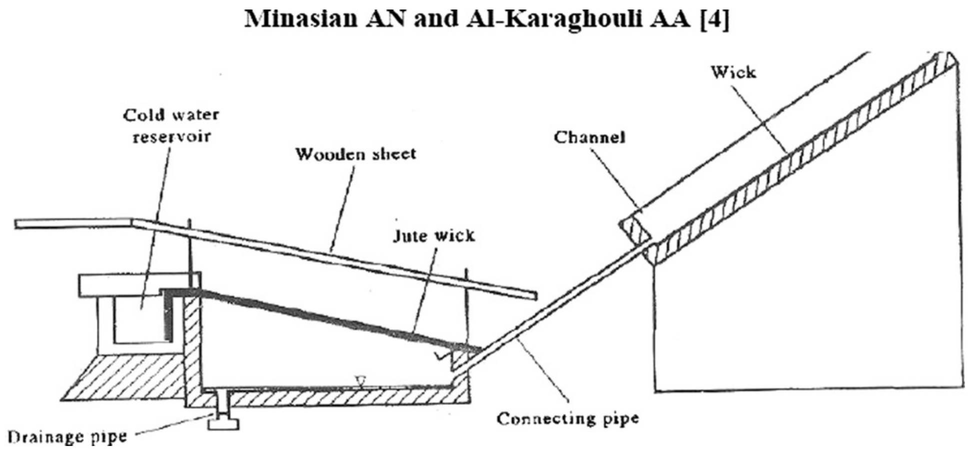

Fig. 2. Wick basin type solar still.

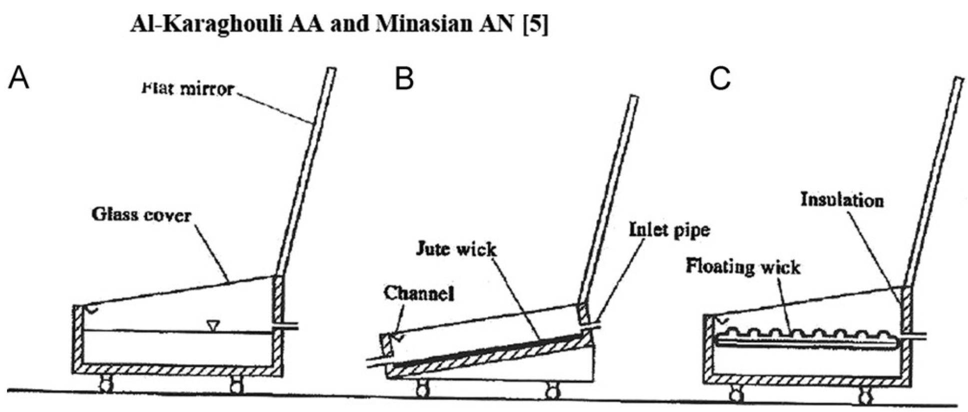

Fig. 3. Experimental still-floating wick-type.

from the following equation:

$$\Delta Y \le \sqrt{\frac{kw}{\frac{\rho_w c_{pw}}{\Delta\tau} - U_2 A_s}} \tag{1}$$

where, $\Delta\tau$ is the selected time interval (2 min).

Then the rate of condensation for each time interval has been calculated for the mean value of meteorological data of solar intensity, wind speed and ambient temperature, as follows:

$$m_{int}(j) = \frac{h_{cond}(T_v - T_{gi})}{\lambda}\Delta\tau \tag{2}$$

and the hourly productivity, m_i, $i=1, 2,...$

$R=3600/\Delta\tau$

If W is the number of operating hours per day, then daily productivity (P_d) is obtained as

$$P_d = \sum_{i=1}^{w} m_i \tag{3}$$

The results found for floating-wick still with blackened jute wick [5] have shown an increase in minimum average value of about 82% and 72% for the tilted wick and floating wicks. The still have shown an increase in productivity by 15% and 40% when the depth of the water is 3 cm and 6 cm respectively [6].

3.1.4. Multi-wick type solar stills

A multi-wick type solar still has great potential because of high productivity, simplicity and less maintenance. It consists of a glass cover, poly-tetrafluoroethylene nets between wicks, stand holding the whole apparatus and similar to that of wick type solar still [7]. The proposed solar still is shown in Fig. 4.

3.1.4.1. Working. The still consists of an evaporating wick, condensing wick and a poly(tetrafluoroethylene) (or PTFE) net sandwiched between them. Water vapor diffuses through the spaces in the net from the evaporating wick to the condensing wick. The sandwiched 2 mm thick PTFE net reduces the gap between evaporating and condensing surfaces considerably, yet prevents contamination of the condensate with saline water due to its very low wettability. This unit has great potential for becoming the base unit in a compact still with superior productivity.

Similarly analytical model of a multi-wick solar still with water flowing over the glass cover have been theoretically proposed by Dhiman and Tiwari [8]. The energy balance conditions for the flowing water, glass cover and absorbing wick surface are given.

$$h_2'(T_g - T_w)bdy = h_2(T_{w1} - T_a)bdy + Q_e\, bdy + m_w c_w \frac{\partial T_{w1}}{\partial x}dy \tag{4}$$

$$h_1(T_w - T_g) = h_2'(T_g - T_{w1}) \tag{5}$$

$$\tau S = h_1(T_w - T_g) + h_b(T_w - T_a) \tag{6}$$

The solutions of Eqs. (5) and (6) gives

$$T_g = \frac{h_{\tau S} + hh_b T_a + h_2 T_{w1}}{h_2 + hh_b} \tag{7}$$

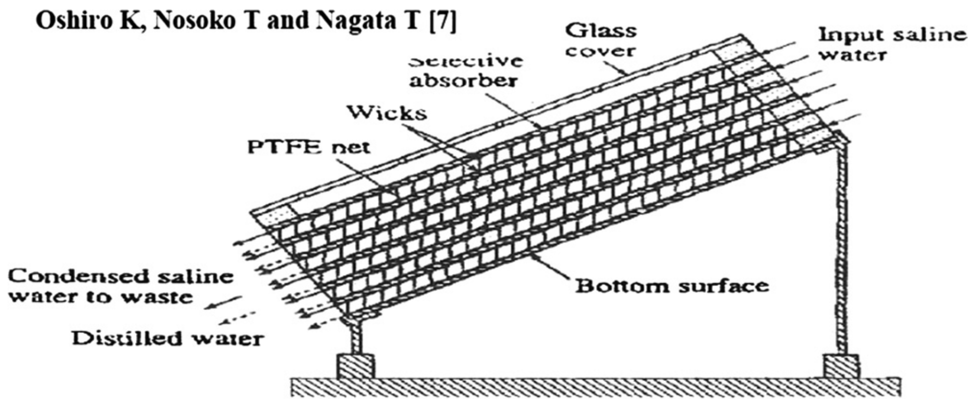

Fig. 4. Multi-wick still with wick/PTFE net/wick layer units.

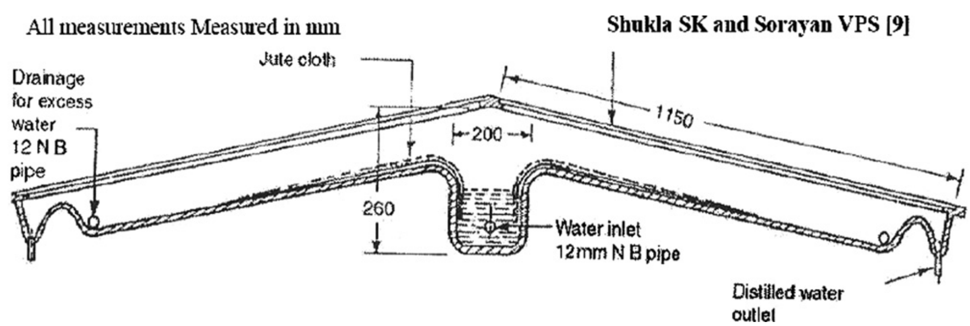

Fig. 5. Schematic representation of a double slope mult wick solar still.

$$T_w = \frac{\tau S + h_1 T_g + h_b T_a}{h_1 + h_b} \tag{8}$$

where

$$h = \frac{h_1}{(h_1 + h_b)} \tag{9}$$

Substituting the above values in Eq. (4), we obtain

$$m_w c_w \frac{\partial T_{w1}}{\partial x} dy = bM_2(M_3 - T_w) \tag{10}$$

Assuming the condition $x=0$, $T_{wf}=T_{ft}$

$$T_{w1} = M_3 - (M_3 - T_{fi})\exp(-Hx) \tag{11}$$

$$T_{w1} = \frac{1}{L}\int_0^L T_{w1} dx \tag{12}$$

The distillate can be found from the expression

$$m_{ew} = \frac{h_{ew}(\overline{T}_w - \overline{T}_g)}{L} \tag{13}$$

where the heat transfer coefficients h_{ew}, h_{rw} h_{cw} have been calculated from the following expressions by Dunkle:

$$h_{cwg} = 0.884 \times \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268900 - P_w} \right]^{\frac{1}{3}} \tag{14}$$

$$h_{rwg} = \frac{\varepsilon\sigma \times (T_w + 273)^4 - (T_g + 273)^4}{(T_w - T_g)} \tag{15}$$

$$h_{ewg} = 0.016273 \times h_{cwg} \tag{16}$$

Similarly Shukla and Sorayan [9] have proposed a multi-wick solar still and shown in Fig. 5. Energy balance equations are similar to the equations by Dhiman and Tiwari [8], with some modifications in the heat transfer equations. By using these expressions in their heat transfers the overall efficiency of the distillate output is obtained from the following expression:

$$\eta_0 = \frac{\sum m_{ew} l + \sum qu}{\sum I(t)} \tag{17}$$

But Shakthivel et al. [10], have proposed their study on regenerative solar still with jute as energy storage medium kept in a vertical position with respect to the bottom surface of the still. The values of heat transfer, based on the present study, are in close agreement with Dunkle's expression, with 9% of deviation.

3.1.5. Floating cum tilted wick type stills

A floating cum tilted wick type solar still is simple in construction. The new tilted cum floating wick type has been proposed by Janarthanan et al. [11,12] which is shown in Fig. 6. In this study, the blackened jute wick is spread along with a 15° tilted portion. The remaining part of the wick has been prepared in a corrugated shape and floated in the water reservoir inside the still with a thermo coal sheet of thickness 2½ cm. The water level in the reservoir is always maintained to stay below the reservoir by 0.25 cm to make sure that the water does not overflow in the tilted portion.

3.1.5.1. Working. The solar radiation falling over the glass cover after transmission is absorbed by the tilted wick and floating wick surfaces. A part of the energy is utilized to heat the water flowing through the wicks due to capillary action. There is a transfer of energy from the tilted wick and floating wick surfaces to the glass cover and to the ambient air by evaporation, convection and radiation.

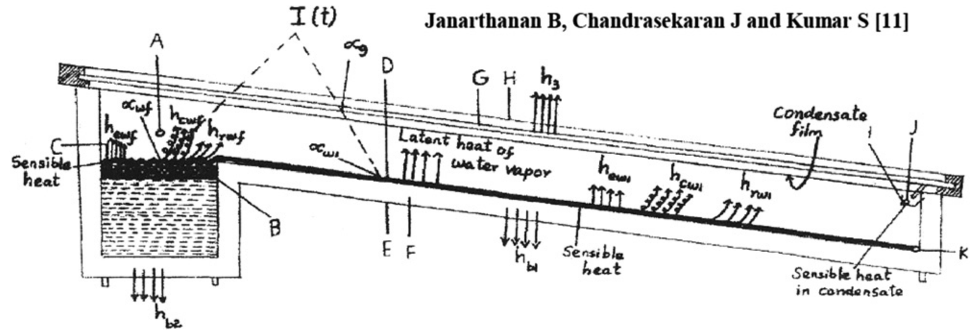

Fig. 6. Sectional view and energy flow diagram for a closed cycle system of a floating tilted wick solar still. (A) Constant water level inlet; (B) thermocole sheet 2½ cm thick; (C) floating wick surface; (D) tilted wick surface; (E) outer plywood; (F) glass wool insulation; (G) glass cover 4 mm thick; (H) wooden frame; (I) distilled water outlet; (J) distilled water collection channel and (K) excess saline water outlet.

This model solves three problems of the previous models. The first problem was the dryness of the wick surface during the sunny hours. This is solved by maintaining the water level in the reservoir by giving in the waste excess hot water during the early and late working hours of the still. This also solves the second problem of heat loss through wasted hot water during late and early hours of the day. The third problem is the salt scale formation, which is solved by folding the remaining part of the wick in a corrugated shape. As the salt stays down in this part of the wick, such salt scale formation is avoided completely.

A theoretical model has been proposed with the following assumptions:

- The transparent glass cover and wick surface are parallel.
- The still is well insulated in the bottom and sides.
- There is no temperature gradient along glass cover.
- The still is leak-proof for vapour.

The energy balance equations have been written for the glass cover, floating wick water surface and tilted wick water surface [11] and include the effect of water flowing over the glass cover and energy balance is written for the same in [12]. The energy balance analysis shows that the total heat transfer taking place throughout each parts of the wick can be found. He proposed theoretical analysis for closed and open cycle systems [11] and water flowing over the glass cover [12]. The energy balances for

Glass cover

$$\alpha_g I(t) b_3 dx_3 + h_1 (T_{w1} - T_g) b_1 dx_1 + h_2 (T_{wf} - T_g) b_2 dx_2 = h_3 (T_g - T_a) b_3 dx_3 \tag{18}$$

For tilted wick water surface

$$\alpha_{w1} I(t) b_1 dx_1 = m_w c_w \left(\frac{dT_{w1}}{dx}\right) dx_1 + h_1 (T_{w1} - T_g) b_1 dx_1 + h_{b1} (T_{w1} - T_a) b_1 dx_1 \tag{19}$$

For floating wick water surface

$$\alpha_{wf} I(t) b_3 dx_3 = m_{wf} c_w \left(\frac{dT_{wf}}{dx}\right) dx_2 + h_2 (T_{wf} - T_g) b_2 dx_2 + h_{b2} (T_{wf} - T_a) b_2 dx_2 \tag{20}$$

For water flowing over the glass cover

$$h(T_g - T_{fw}) b_3 dx_3 = m_w c_w \left(\frac{dT_{fw}}{dx}\right) dx_3 + \left[h_4 (T_{wf} - T_a) + \theta_{evap}\right] b_3 dx_3 \tag{21}$$

The overall efficiency of these stills are defined as follows:

$$\eta\% = \frac{h_{ew1} (\overline{T}_{w1} - T_a) A_{w1} + h_{ewfa} (\overline{T}_{wf} - T_a) A_{wf}}{I(t)} \times 100 \tag{22}$$

3.1.6. *Tilted wick-type solar still with flat plate reflector*

A tilted wick type solar still with flat plate reflector, proposed by Tanaka and Nakatake [13] is simple in construction. It consists of a glass cover, tilted-glavanized iron tray, wick material and a flat plate reflector to improve the amount of distillate output for different seasons of the year. The still is completely reviewed by Kaushal and Varun [24].

Similarly, Tanaka and Nakatake [14–17] have studied the increase in distillate output of a tilted wick type solar still with inclined external flat plate reflector [14], with one step azimuth tracking of a tilted wick solar still [15], tilted wick type still with bottom reflector [16] and tilted wick still for the determination of optimum inclination and influence of the reflector[17].

An external reflector can be a useful and inexpensive modification to increase the distillate productivity of single effect stills. Here in this study [14], the reflector length is half of, or same as, the still's length. The reflector inclination has been set at about 15° from vertical which increased length of the still. The solar radiation reflected from the reflector and absorbed on the wick, $Q_{sun,re}$ can be determined as

$$Q_{sun,re} = G_{dr} \frac{l_4}{l_1} \tau g(\beta) \rho_m dw \times l_1 \left\{ w - \frac{1}{2}(l_2 + l_3) \right\} \tag{23}$$

3.1.6.1. *Working.* As mentioned in [15], the still is subjected to one step azimuth tracking once in a day i.e., the tilt angle of the still θ, orientation of the still γ were adjusted once in a day. The orientation is $-45°$ (south–east) during morning and it is changed to 45° (south–west) during noon. This one step azimuth manual tracking showed a better optimum angle studies for the tilted wick type stills under various climatic conditions.

But in the case of bottom reflector, the reflected solar radiation and its absorption over the wick can be determined as

$$Q_{sun,re} = G_{dr} \frac{l_4}{l_1} \tau_g \left(\beta'\right) \rho_m \alpha w \times (l_1 + l_4) \{ w - 0.5(l_2 + l_7) \} \tag{24}$$

$$\cos \beta' = \sin\phi \, \cos\theta_s + \cos \phi \sin\omega_1 \, \cos \varphi \tag{25}$$

The direct solar radiation absorbed on the wick

$$Q_{sun,dr} = G_{dr} \tau g(\beta) \alpha w \times w l_s (\cos\theta_s + \sin\theta_s + \tan \phi) \tag{26}$$

where β is the incident angle of sun rays to the glass cover.

$$\cos \beta = \sin \phi \cos\theta_s + \cos \phi \sin\theta_s \cos \varphi \tag{27}$$

$$wl_s(\cos\theta_s - \sin\theta_s \cos\varphi/\tan\phi) \quad (28)$$

The diffused solar radiation on the wick surface $Q_{sun,df}$ can be determined as

$$Q_{sun,df} = G_{df}(T_g)_{df}\alpha w \times wl_s \quad (29)$$

where Gdf is the diffused solar irradiance on the horizontal surface. $(T_g)df$ is the function of the inclination of the collector.

The heat and mass transfers for the still have been proposed by writing energy balance equations for the glass cover and evaporating wick surface as follows:

$$Q_{sun,g} + Q(r+d+e)_{w-g} = Q(r+c)_{g-a} + mcp_g \frac{dT_g}{dt} \quad (30)$$

$$Q_{sun,w} = Q(r+d+e),_{w-g} + Q, d,_{w-a} + Q_f \quad (31)$$

The solar radiation absorbed on the glass cover and the evaporating wick are determined as

$$Q_{sun,g} = \left(\frac{Q_{sun,dr}}{T_g(\beta)} + \frac{Q_{sun,re}}{T_g(\beta')} + \frac{Q_{sun,df}}{(T_g)_{df}}\right) \times \frac{\alpha_w}{\alpha_g} \quad (32)$$

$$Q_{sun,w} = Q_{sun,dr} + Q_{sun,df} + Q_{sun,re} \quad (33)$$

The variations of the daily amount of distillate, and the *increase ratio* with a reflector inclination θm for RS on four days (the spring and autumn equinox and summer and winter solstice) have been found as follows:

$$\text{Increase ratio} = \frac{\text{Daily amount of distillate of RS}}{\text{Daily amount of distillate of NS}} \quad (34)$$

The study concluded that the bottom reflector can reflect the sun rays to the evaporating wick and increase the distillate productivity during summer by (25%) and in winter by (10%). In another study with external flat plate reflector to a tilted wick type solar still, the optimum inclination of still and reflector has been proposed [17]. The optimum inclination of the still is 10° in summer and 50° in winter. And the inclination of the still and the reflector has shown 21% difference in daily distillate than conventional stills (Fig. 7).

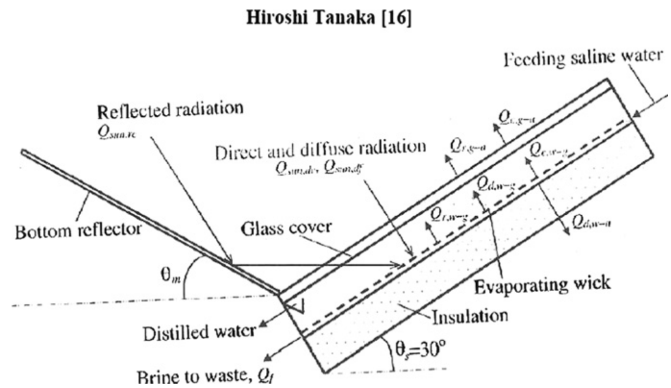

Fig. 7. Wick type still with top and bottom reflector.

3.1.7. "V" type solar still with charcoal absorber

Selvakumar et al. [18] have proposed a "V" type solar still with charcoal as absorbing material. The construction of the still is simple and it consists of galvanized iron tray, glass cover, charcoal absorber, boosting mirror and water collection segment which is shown in the Fig. 8. In this study, the heat transfer taking place inside the still, outside the still and the performance of the still have been calculated with the help of Nusselt (Nu) and Grashof number (Gr).

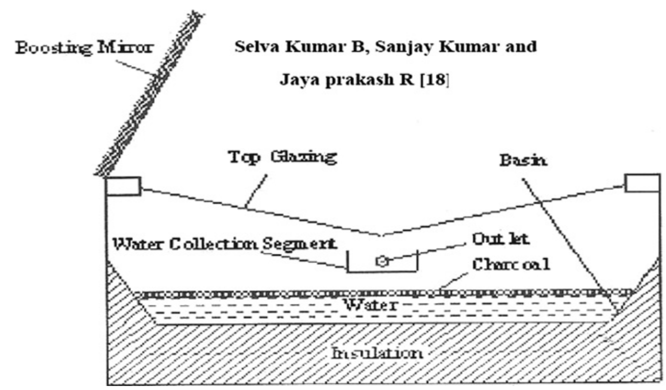

Fig. 8. "V" type solar with charcoal absorber.

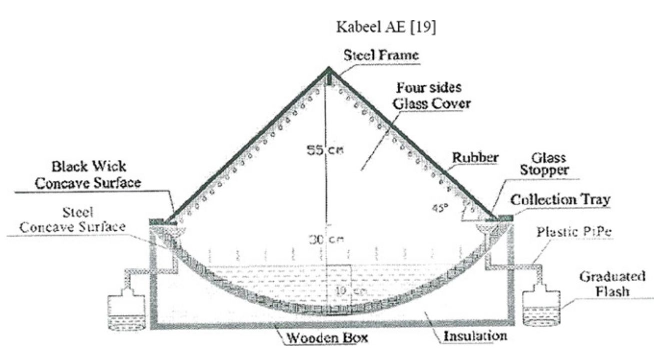

Fig. 9. Concave wick type solar still.

3.1.7.1. Working.

Two modes of heat transfer takes place in the still and they are

Internal heat transfer mode. In the internal heat transfer mode, heat is transported inside the still by free convection of air. It releases its enthalpy in air which is coming in contact with the glass cover, the heat transfer per unit area in unit time due to convection have been calculated.

$$Q_{ci} = h_{ci}(T_w - T_g) \ \text{w/m}^2 \quad (35)$$

The heat transfer mode inside the still due to evaporation is given by

$$Q_{ei} = h_{ei}(T_w - T_g) \ \text{w/m}^2 \quad (36)$$

Similarly heat transfer for radiation is given as

$$Q_{ri} = h_{ri}(T_w - T_g) \ \text{w/m}^2 \quad (37)$$

The computation ratio(s) is given by

$$Si = \frac{h_e}{h_e + h_{cw} + h_{rw}} \quad (38)$$

Heat transfer outside the still. Heat transfer per unit area per unit time is given by

$$Q_{ac} = h_{ca}(T_g - T_a) + \varepsilon_g\left[(T_g+273)^4 - (T_{sky}+273)^4\right]\ w/m^2 \quad (39)$$

The heat loss through the base is a must to identify the performance, so that

$$Q_{be} = h_{be}(T_w - T_{amb}) \quad (40)$$

The efficiency of the system with the boosting mirror have been calculated as

$$\eta = \left[\frac{Mh_o}{h_s(A+A_m)t}\right] \quad (41)$$

where $A_m = 0$

The results show that the charcoal absorber has increased the absorption of radiation in water resulting in the increase of evaporation rate. Also the boosting mirror had increased the evaporation further.

Performance of a solar still with a concave wick evaporation surface has been proposed by Kabeel [19]. The construction of the still is different from other types of stills and the schematic representation is shown in Fig. 9. The working of the still is like that of the normal wick type solar still and the advancement used in this type of still is, the concave wick arrangement and the four side condensing covers. Use of glass covers at four sides of the still reduces the shading effect compared with that of conventional solar still. This study has shown that the instantaneous efficiency is 45%, and average daily efficiency is 30% more than conventional type stills.

3.1.8. Fin type solar stills

Velmurugan et al. [20] have studied a single basin solar still with fin for enhancing productivity with three different types of modified still with three different absorbing materials (i.e.,) wick, sponge pieces and fins of equal sizes have been used.

The three types of the still are easy to construct and they contain glass cover, galvanized sheet iron tray, absorbing materials,

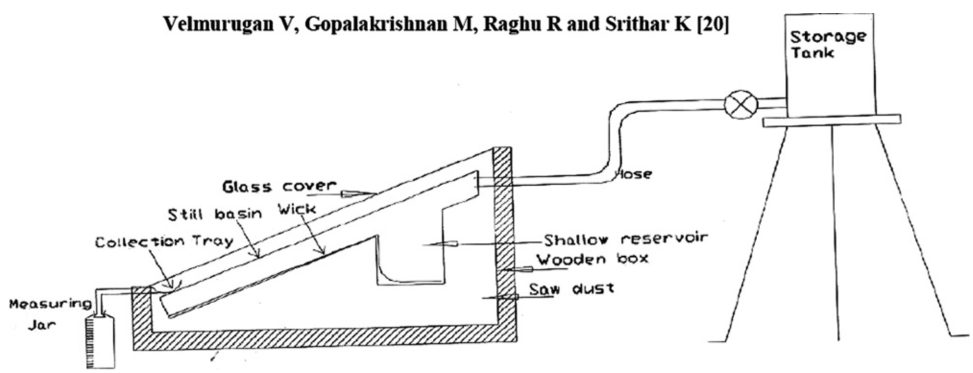

Fig. 10. Schematic diagram of wick type solar still.

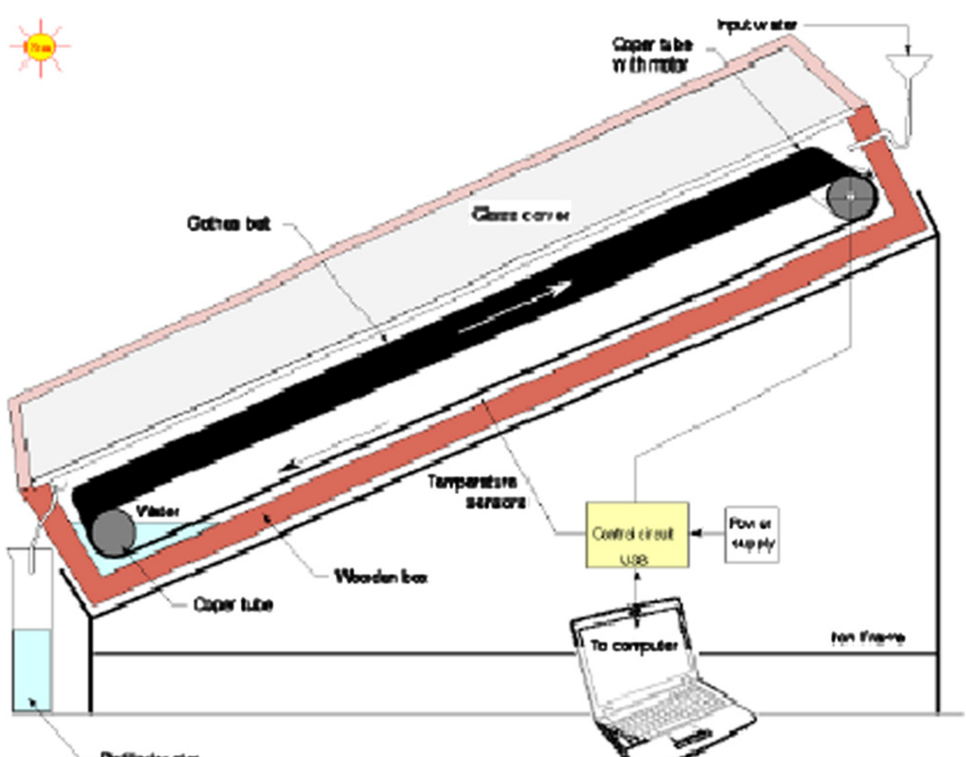

Fig. 11. Clothes moving wick type solar still.

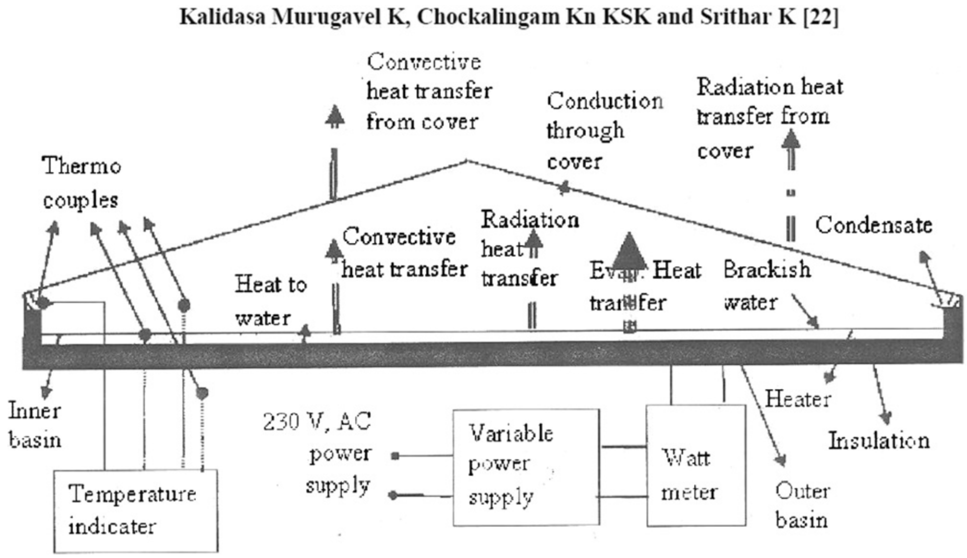

Fig. 12. Single basin double slope simulation still.

wooden box covering the still, and a tilted tray for tilted wick type solar still. The evaporative area is 1 m^2 when the still is without fin and the basin area was 1.0045 m^2 when fins were used. The schematic representation of the still using wick materials as absorber is shown in Fig. 10.

Sponge type. Due to capillary force, sponges absorb more water. Thus exposure area increased. This leads to increase in evaporation rate. The productivity of the still has increased by about 15.3% when sponges were used. The maximum deviation between experimental and theoretical analysis was less than 6.2%.

Wick type. The productivity of the still has increased by around 29.6% when wicks were used in the still. The theoretical and experimental values agreed with a deviation of 10.8%.

Fin type. As fins are used at the bottom of the still, absorber plate can absorb more solar radiation due to increase in exposure area, and preheating time for saline water has been decreased. The productivity is found to be increased by 45.5% when fins were used. It has a maximum deviation of 9.2% when experimental values are compared with the theoretical.

3.1.9. Clothes moving wick-type solar still

Helmy et al. [21], have proposed a new model for distillation in which the still consists of glass cover, clothes belt, wooden box with insulation, DC motor for rotating the clothes by connecting it to the copper tube, with mirror on one side and without mirror on the other side, as shown in Fig. 11.

3.1.9.1. Working. The input water enters the still through an inlet. The clothes wick is immersed in water when the motor is ON, and the wet clothes are subjected to solar radiation when the motor is OFF. The black cloth is fixed on two copper rollers and a belt. The lower roller is free, while the upper roller is fixed with a high torque motor. Another main component of the system is microcontroller PICI8F2455 from a microchip company. This microcontroller provides the facility of connecting it to a computer via USB (Version 2.0) interface. Its speed is 12 Mb/s and it has been used for high speed data transfer between the computer and the microcontroller.

The experiments were performed at different motor OFF-periods, 5, 10, 20, 30, 40, 50 and 60 min. It was found that the thermal efficiency increases to a maximum when the motor OFF-period was 25 min. This work proves that, the operation of this type of solar still with the computer have reduces the cost of production of distilled water.

The thermal efficiency of the still for a particular period, η is defined by

$$\eta = \frac{m_w L}{A \int_0^{\Delta D} G dt} \tag{42}$$

where

m_w—is the total mass of distilled water collected during this period, kg.

L—latent heat of evaporation at the glass temperature, kJ/kg.

A—area of the clothes wick, m^2.

Δ—Operation period, s.

G—Solar radiation on tilted surface, w/m^2.

t—is the time, s.

3.1.10. Single basin double slope simulation solar still

Kalidasamurugavel et al. [22] have proposed the single basin double slope solar still. The double slope has been tested for a single basin solar still because of lower productivity of single slope, single basin solar stills. The stills productivity depends on parameters like solar radiation, wind velocity, atmospheric temperature, basin water depth, glass cover material, thickness, its inclination and the heat capacity of the still. The still is very easy to construct, and consists of a basin made of mild steel, inner basin, outer basin, two glass covers enclosing the still and tight insulation (rice husk). This is shown in Fig. 12.

The performance of the still is justified with absorbing materials like light cotton cloth, light jute cloth, sponge, quartzite rock and washed natural rock. It was found that light cotton cloth has its maximum production rated value than any other materials. As the rate of rise of temperature is higher for the still with light cotton cloth as basin material during heating and reaches a maximum value at around 1:00 pm.

4. Discussion

Table 1 shows the comparisons of different types of wick type solar stills used for fresh water production from saline or brackish water. The wick type stills have fascinating effect depending on their own utilities and for which they have been used. In Table 1, comparison on five topics have been carried out, i.e. type of the still, geometry, results, advantages and their disadvantages during practical observations.

5. Conclusions

Based on the theoretical and experimental results of various wick type solar stills under various climatic conditions, researchers have considered wick type stills as a leading and economic option for the production of fresh water. Among the wick type solar stills, the floating wick type solar still by Al-karaghouli and Minasian [5] have provided the maximum yield. The regenerative effect i.e., with an optimum water flow rate of 1.5 m/s over the condensing glass cover [8] enhanced the productivity of floating cum tilted-wick type solar still in significant manner. Furthermore, jute wick and charcoal wick [3], cotton cloth [22] and floating perforated black aluminium plate [6] as an absorber medium in the basin have fascinating effect on the productivity of the still.

The review representing the specific inferences drawn from the analysis of wick-type solar still by various authors will pave a way to the researchers to grasp the previous designs and to fabricate a new design with optimum design parameters for higher distillate output.

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